High average power 1314 nm Nd:YLF laser, passively Q-switched with V:YAG

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A 1314 nm Nd:YLF laser was designed and operated both CW and passively *Q*-switched. Maximum CW output of 10.4 W resulted from 45.2 W of incident pump power. Passive *Q*-switching was obtained by inserting a V:YAG saturable absorber in the cavity. The oscillator delivered a maximum of 825 μJ energy per pulse, with a pulse duration of 135 ns at a pulse repetition frequency of 6.3 kHz, effectively delivering 5.2 W of average power.

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High-power 1.3 μm lasers have a wide range of applications, which include communications, sensing, timing systems, and monitoring techniques. The 1.3 μm output can be Raman-shifted to the 1.5 μm region, which is useful for applications requiring eye-safe operation at high powers, such as Lidar and free-space optical communication [1]. Furthermore, 1314.0 nm (specifically the 657.0 nm harmonic) is required to probe the relevant transition [2] for optical calcium clocks.

The main 1.3 μm emission lines of Nd:YLF are at 1314 nm for the σ polarization and 1321 nm for the π polarization. To our knowledge, the highest 1.3 μm CW output power reported from a diode-end-pumped Nd:YLF laser is 6.2 W [3], which leaves room for power scaling as was done for 1.0 μm Nd:YLF [4,5], or 1.3 μm Nd:YAG, and Nd:GdVO$_4$ [6,7] lasers. Operating an end-pumped Nd:YLF laser at 1.3 μm is attractive because of the weak thermal lens when it is operated on the σ polarization [8,9]. This results in excellent beam quality over a wide range of output powers.

Nd:YLF also has a long upper-laser-level ($^4F_{3/2}$) lifetime of $\tau \sim 520$ μs compared to ~250 μs for Nd:YAG and ~100 μs for Nd:YVO$_4$ [10,11]. The resulting high energy storage capability makes Nd:YLF suitable to generate high pulse energies during *Q*-switched operation. However, the emission cross section σ_{em} at 1.3 μm for Nd:YLF is ~2–2.5 × 10^{-20} cm^2 (for the two polarizations), which is a factor of three less than that of Nd:YAG and an order of magnitude less than that of Nd:YVO$_4$ [11], which implies lower gain.

Power scaling Nd lasers at 1.3 μm are more difficult than at 1.0 μm because of the lower σ_{em}. The relatively longer lifetime τ of Nd:YLF partially compensates for this. The σ_{em} and τ values of Nd:YLF also necessitate a careful design of the pump beam radius where a trade-off has to be made between a reasonably low threshold and the risk of thermal fracture [5]. Thermal effects are especially problematic under 1.3 μm operation (compared to 1.0 μm operation) due to the larger quantum defect. By using a relatively low Nd doping, one can reduce upconversion and spread out the thermal load longitudinally in the crystal, which increases the thermal fracture pump limit [4,5,12].

Nd-doped active media are suitable for an efficient *Q*-switched operation at 1.3 μm using a V:YAG saturable absorber because they have a high ratio $\alpha = \sigma_{\text{GSA}}/\sigma_{\text{em}}$, with σ_{GSA}, the ground-state absorption cross section of the saturable absorber and σ_{em} the emission cross section of the laser crystal [13]. It has been demonstrated that V:YAG operates efficiently as a saturable absorber for Nd lasers operating in the 1.0 and 1.3 μm bands. Nd:YAG, Nd:YVO$_4$, Nd:YAP, Nd:KGW, Nd:GdYVO$_4$, and Nd:GGG have previously been passively *Q*-switched with V:YAG at 1.3 μm [13–21]. To the best of our knowledge, V:YAG has not been used to passively *Q*-switch Nd:YLF lasers at either 1.0 or 1.3 μm. Considering other diode end-pumped 1.3 μm Nd lasers passively *Q*-switched with V:YAG, the highest average power was 2.1 W for Nd:YVO$_4$ [13] while Nd:YAG delivered the highest energy per pulse of 126 μJ and peak power of 6.1 kW in different setups [18]. Nd:YLF has the potential to significantly increase the pulse energy due to its longer upper-laser-level lifetime [5,22].

Here we demonstrate high-power 1314 nm operation of a diode end-pumped Nd:YLF laser in both CW and passively *Q*-switched modes.

The linear two mirror resonator (Fig. 1) consists of a 300 mm concave input coupler (IC) mirror which is highly reflective at 1314 nm and is highly transmissive

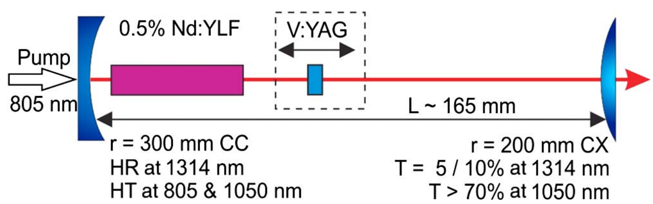

Fig. 1. (Color online) Experimental resonator layout for CW and a passively *Q*-switched (with V:YAG) operation.

at 805 nm. Two 200 mm convex output couplers (OCs) with transmissions of 5% and 10% at 1.3 μm were available and placed ~165 mm from the IC. Operation was forced onto the 1.3 μm line by specifying both the IC and OC to be highly transmissive at ~1 μm. The size of the fundamental laser mode in the crystal was adjusted at full pump power to match the pump beam by adjusting the position of the OC.

The laser crystal consisted of a single 0.5% doped a-cut Nd:YLF rod which was 5 mm in diameter and 30 mm in length. It was mounted in a water-cooled copper block with its *c*-axis horizontally and was placed next to the IC. The laser crystal was end-pumped from one side with a fiber-coupled diode laser module (Jenoptik JOLD-140-CAXF, 0.6 mm, 0.22 NA fiber, ~805 nm) with the pump power limited to ~45 W to avoid thermal fracture. The pump beam was focused to a waist radius of ~700 μm in the center of the gain medium and had a roughly bell-shaped energy distribution. This waist radius was determined with a gain optimization method similar to the one described in [5] because both the pump and laser beam radii have a strong influence on the gain as well as on the thermal load. In this method, we also set the parameters so that the threshold would be at about 25% of the maximum pump power.

The CW slope efficiencies of the oscillators with the two OCs are shown in Fig. 2. The most efficient CW operation, as well as highest output power, was achieved with a 5% OC with a resulting slope efficiency of 29%. This laser had an incident pump power threshold of 9.25 W and a maximum power output of 10.4 W, which is 1.7 times higher than recently reported [3]. The beam had a symmetrical Gaussian profile, but at the maximum pump power the beam became slightly elliptical with the horizontal radius being ~25% larger than the vertical. This was due to the YLF's astigmatic thermal lensing [23]. Wavelength measurements showed oscillation only at 1314 nm on the σ polarization due to the oscillator being unstable for the stronger negative thermal lenses associated with the π polarization [8,9].

The 5% OC oscillator was subsequently passively Q-switched by inserting a 3 mm thick V:YAG saturable absorber with an initial single pass absorption of ~3% in the cavity between the gain medium and OC (Fig. 1). The V:YAG crystal was cut along [111] to avoid anisotropy. Initial experiments indicated that the pulsed performance at various input powers was relatively insensitive to the position of the V:YAG Q-switch and the Q-switch was subsequently placed ~12 mm from the Nd:YLF crystal. The incident pump-power threshold of the Q-switched laser was 17.5 W, and the maximum average output power was 5.2 W at an incident pump power of 45.2 W (Fig. 3). As the incident pump power was increased from threshold to 27 W, the pulse repetition frequency (PRF) increased from 650 Hz to 5.9 kHz, after which the PRF stayed nearly constant at ~6.3 kHz with increasing incident power (Fig. 3). Thermal lensing of both the Nd:YLF and V:YAG crystals change the laser-beam size within the resonator, which in turn influences the bleaching properties of the V:YAG crystal. This gives rise to a nonlinear behavior in the pulse repetition rate [24]. The constant PRF over a range of high powers may be a desirable characteristic for some applications.

Pulse duration at full width at half-maximum decreased from 162 to 136 ns with increasing pump power (Fig. 4). The increase in average output power and almost constant PRF above 27 W resulted in an increase in pulse energy up to 825 μJ (Fig. 4) with a peak power of 6.1 kW. Energy per pulse and average power was higher than previously reported with other diode-end-pumped

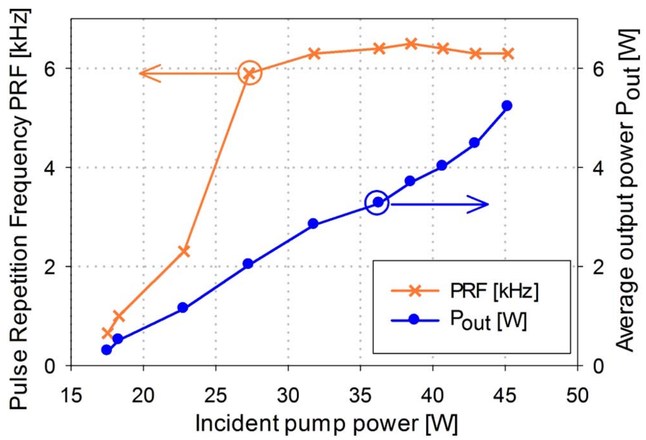

Fig. 3. (Color online) Passively Q-switched behavior: PRF (left axis) and average output power (right axis).

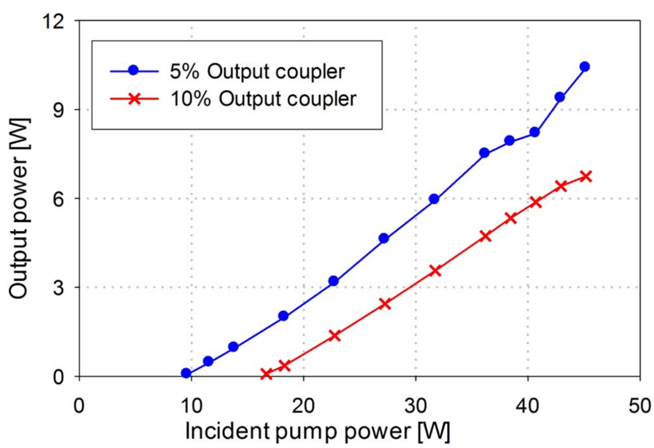

Fig. 2. (Color online) Slope efficiencies of the CW laser for the different OCs used.

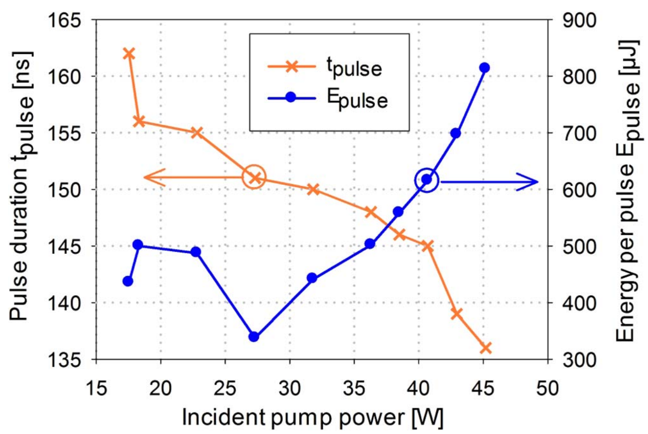

Fig. 4. (Color online) Passively Q-switched behavior: pulse duration (left axis) and energy per pulse (right axis).

passively Q-switched 1.3 μm Nd lasers with V:YAG: by 6.5 times (126 μJ with Nd:YAG) [18]) and 2.5 times (2.1 W with $Nd:YVO_4$ [13]), respectively.

In conclusion, high average power 1314 nm oscillation of an Nd:YLF laser was demonstrated for CW operation and delivered up to 10.4 W of output power. Passively Q-switched operation of an Nd:YLF laser using a V:YAG saturable absorber was demonstrated for the first time. Pulsed operation delivered 825 μJ of energy per pulse with a pulse duration of 135 ns and an average power of 5.2 W. These results are, to the best of our knowledge, the highest reported values for all diode-end-pumped passively Q-switched 1.3 μm Nd lasers with V:YAG.

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